Septal deviation and nasal resistance: An investigation using virtual surgery and computational fluid dynamics

Guilherme J.M. Garcia, Ph.D.,[1] John S. Rhee, M.D., M.Ph.,[2] Brent A. Senior, M.D.,[3] and Julia S. Kimbell, Ph.D.[1,3]

ABSTRACT

Background: *Septal deviation is an extremely common anatomic variation in healthy adults. However, there are no standard criteria to determine when a deviated septum is clinically relevant. Presently, selection of patients for septoplasty is based on mostly clinical examination, which is prone to observer bias and may lead to unsuccessful treatment. The objective of this article is twofold. First, we investigate whether the location of a septal deviation within the nasal passages affects nasal resistance. Second, we test whether computer simulations are consistent with rhinomanometry studies in predicting that anterior septal deviations increase nasal resistance more than posterior deviations.*

Methods: *A three-dimensional computational model of a healthy nose was created from computed tomography scans. Geometry-deforming software was used to produce models with septal deviations. Computational fluid dynamics techniques were used to simulate nasal airflow and compute nasal resistance.*

Results: *Our results revealed that the posterior nasal cavity can accommodate significant septal deviations without a substantial increase in airway resistance. In contrast, a deviation in the nasal valve region more than doubled nasal resistance. These findings are in good agreement with the rhinomanometry literature and with the observation that patients with anterior septal deviations benefit the most from septoplasty.*

Conclusion: *In the model, anterior septal deviations increased nasal resistance more than posterior deviations. This suggests, in agreement with the literature, that other causes of nasal obstruction (dysfunction of the nasal valve, allergy,* etc.*) should be carefully considered in patients with posterior septal deviations because such deviations may not affect nasal resistance. This study illustrates how computational modeling and virtual manipulation of the nasal geometry are useful to investigate nasal physiology.*

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Key words: Computational fluid dynamics, computer simulations, deviated septum, human nose, nasal airflow, nasal obstruction, nasal resistance, rhinomanometry, septoplasty, virtual surgery

Chronic nasal obstruction has various etiologies, including septal deviation, turbinate hypertrophy, and incompetence of the nasal valve. Because septal deviation is so common (studies of cranial computed tomography [CT] scans reveal an incidence in healthy adults of 19.5–26%),[1–5] clinicians must often decide whether the septal deviation detected on physical examination is the cause of nasal obstruction or a normal anatomic variation. Currently, there are no standard criteria to determine when a septal deviation is clinically relevant. The long-term objectives of this study are to clarify the role of septal deviations in increasing nasal resistance and then to examine the potential of computer simulations to predict nasal resistance *in vivo* and, consequently, to plan surgical approaches that minimize nasal resistance. As a first step to achieve these goals, this study aims to (1) test whether the location of a septal deviation affects nasal resistance and (2) test whether computer simulations are consistent with past rhinomanometry studies.

Surgical correction of septal deviations (septoplasty) is one of the most common procedures in otolaryngology, although the objective evidence to support the efficacy of this form of surgery is controversial.[2,6–9] Short-term studies have found patient satisfaction rates ranging from 63 to 88%.[2,9–11] However, studies with a more prolonged follow-up have suggested a gradual deterioration in patient satisfaction.[8,12] Jessen and collaborators[12] found that only 26% of their patients were symptom free 9 years postoperatively. Ho and colleagues[8] observed that the percentage of patients with >50% reduction in the subjective feeling of obstruction decreased from 73% to 60% to 41% and then to 27% at 3 months, 6 months, and 1 year, and 2.5 years postoperatively. It has been suggested that the higher success rates of short-term studies may be a placebo effect.[2,7,8]

Recently, Singh and colleagues[6] conducted a systematic review and meta-analysis of the literature on septoplasty. Despite the abundant literature on this topic, these authors found only three articles that fulfilled certain credibility criteria, which included the use of at least one objective method (rhinomanometry or acoustic rhinometry) to evaluate the surgical outcome. Their analysis suggested that septoplasty reduces nasal resistance in most patients. However, these authors were startled by the small number of articles that met their eligibility criteria and concluded that more standardized, long-term studies are needed to sustain a definitive, objective argument in favor of septal surgery.[6]

Traditionally, the decision to perform septoplasty usually relies on clinical observations alone.[7] Selection for surgery is challenging in many patients because there are no agreed criteria by which to decide how much a septum should be deviated before surgery is indicated.[2,6] Rhinomanometry and acoustic rhinometry have been tested as possible objective methods to evaluate nasal airflow and select patients for surgery, but conflicting results have been reported. Although some authors found a significant correlation between objective and subjective measures of airflow,[11,13–18] others found poor correlation and concluded that rhinomanometry and acoustic rhinometry are not useful to select patients for surgery.[8,9,19–22] In their critical review of the literature, Robin and Eccles[2] concluded that little progress in understanding the involvement of septal deviations in nasal disease will be made until a better objective method is developed to quantify the degree of septal deviation and its impact in nasal physiology.

The objective of this article is twofold. First, we investigate how nasal resistance is affected by the location of a septal deviation. We use shape-deforming software and a three-dimensional (3D) com-

From [1]The Hamner Institutes for Health Sciences, Research Triangle Park, North Carolina, [2]Department of Otolaryngology and Communication Sciences, Medical College of Wisconsin, Milwaukee, Wisconsin, and [3]Department of Otolaryngology/Head and Neck Surgery, University of North Carolina, Chapel Hill, North Carolina
Current Address of Guilherme Garcia, Ph.D., is Department of Pharmacology, University of North Carolina, Chapel Hill, North Carolina
Funded by the American Chemistry Council (United States) and CNPq (Brazil)
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Address correspondence and reprint requests to Guilherme Garcia, Ph.D., Department of Pharmacology, University of North Carolina, CB7365, 120 Mason Farm Road, Chapel Hill, NC 27599
E-mail address: guilhermejmgarcia@gmail.com
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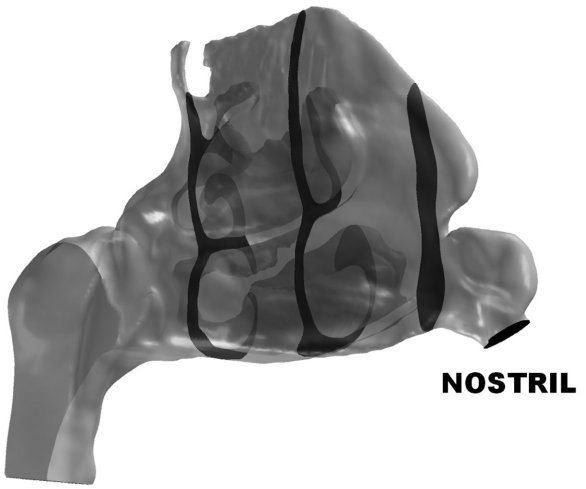

Figure 1. *Three-dimensional reconstruction of the left nasal passage of a healthy subject. This geometry was the cornerstone to create models with simulated septal deviations. The three highlighted coronal planes (anterior, middle, and posterior planes) show where septal deviations were created (see Fig. 4).*

puter model of a normal nose to create septal deviations in different locations of the nasal airway. The effect of septal deviations on nasal resistance is investigated using computational fluid dynamics (CFD). Second, we test whether computer-derived nasal resistance is consistent with *in vivo* observations. Recently, computational modeling of nasal airflow has advanced significantly and it has been suggested that CFD techniques can be used as a surgical planning tool to predict the outcome of nasal surgery.[23] However, most studies have focused on describing nasal filtration,[24–26] nasal airflow patterns[27–30] or air conditioning,[31–33] and only a few studies[34–38] attempted to correlate computational parameters to nasal symptoms. The present study is a first step toward validating computational modeling as a tool to estimate nasal resistance. In other words, this work is a proof-of-concept study to show that computational models and virtual manipulation of the nasal anatomy may provide realistic predictions of nasal resistance, supporting the view that virtual planning of nasal surgery is feasible.

METHODS

A 3D model of the left nasal passage (Fig. 1) of a 37-year-old woman (white; body mass, 56.7 kg; height, 1.73 m) was created as follows. The patient had been scanned to check for possible mucosal thickening, but the computed tomography (CT) scans revealed a normal nasal anatomy with clear sinuses. The use of this data set in this research project was approved by the Office of Human Research Ethics of the University of North Carolina (Chapel Hill, NC). The CT scans were obtained *via* a Sensation 16 CT scanner (Siemens, Chicago, IL) with a slice thickness of 1.0 mm, a distance between cuts of 0.70 mm, and a pixel resolution of 0.39 × 0.39 mm. The CT scans were imported into a medical imaging software (Mimics; Materialise, Ann Arbor, MI), where the 3D anatomy of the left nasal passage was manually selected. The paranasal sinuses were manually removed from the geometry to focus on airflow in the main nasal chamber.

To solve the equations that govern fluid flow, the geometry must be divided in a large number of small cells where the variables (air velocity, pressure, *etc.*) can be defined. This was accomplished by creating a mesh with tetrahedral cells in ICEM-CFD (Ansys, Canonsburg, PA). The quality of the tetrahedra was checked to ensure that all cells had an aspect ratio of >0.3, a value needed to avoid

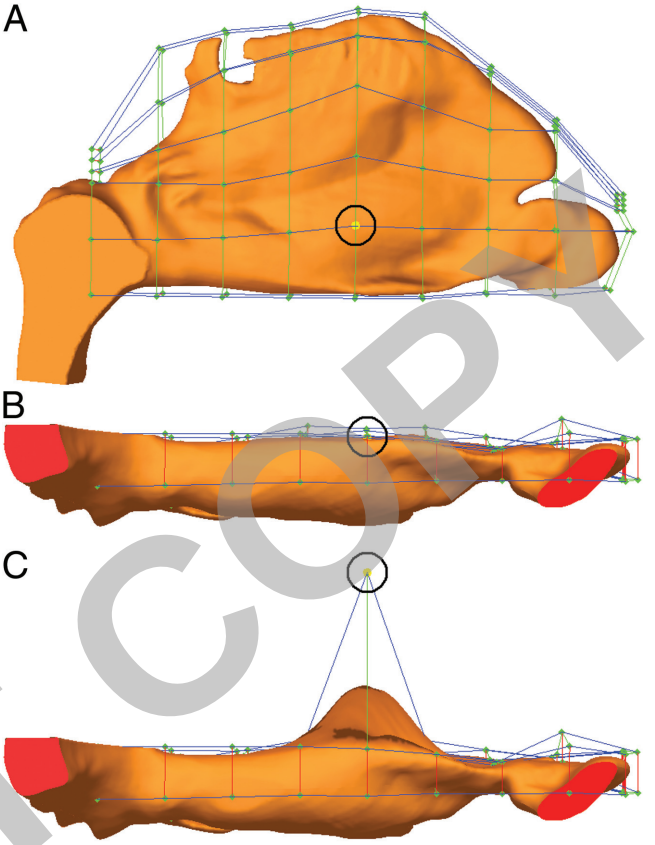

Figure 2. *Illustration of the geometry deformation in the software Sculptor. Control points are created encompassing the region to be deformed (i.e., the septal wall). Once the control points are mathematically linked to the nasal geometry, septal deviations are created by manipulating the control points. For visualization purposes only, the figure displays the septal wall being pulled away from the lateral wall by moving the encircled point. (A) Septal view before deformation. (B) Inferior view before deformation. (C) Inferior view after deformation.*

distorted elements and optimize the accuracy of the numerical simulations. A mesh density study revealed that a mesh with 967,000 elements provided results that were independent of mesh density. The nasal cavity was modeled as a rigid structure.

Simulated septal deviations were created using the mesh-deforming software Sculptor 1.8.4 (Optimal Solutions Software, LLC, Idaho Falls, ID). Sculptor allows the user to deform the mesh in three dimensions while still preserving mesh quality. This software is used in the aircraft and automobile industries, where it is a cost-effective strategy to investigate how geometry affects performance. In theory, Sculptor should preserve mesh quality and eliminate the need to remesh the geometry after the deformation. However, because of the narrow, slit-like nature of the nasal passages, we found that it was difficult to deform the nasal geometry without losing mesh quality. To solve this problem, the models were sent back to ICEM-CFD after creation of the septal deviations to generate high-quality meshes, all of which had ~1 million tetrahedral cells. Therefore, Sculptor was used as a cost-effective method to create local deformations of the nasal geometry that mimicked septal deviations (Figs. 2 and 3). The alternative would have been to edit the 3D reconstruction manually, cross-section by cross-section, which would have been very labor intensive.

Septal deviations were created in nine different locations. The lateral wall of the nose was kept at a fixed position, while the septal wall was moved toward the lateral wall to create a local constriction.

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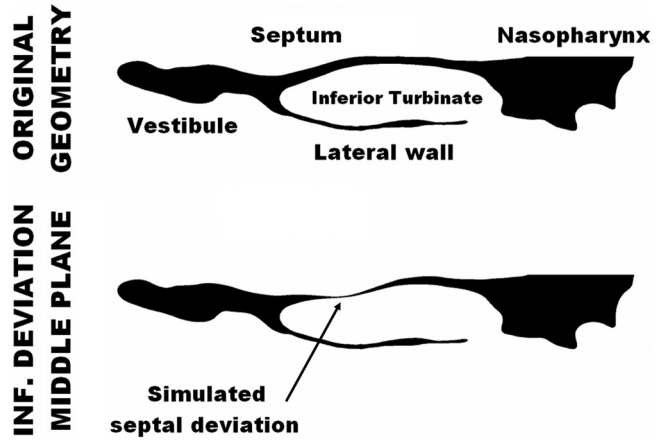

Figure 3. The simulated septal deviations were local constrictions in the airway. (Top) Axial cross-section of the original geometry at the level of the inferior turbinate. (Bottom) The same axial cross-section in the model with an inferior septal deviation in the middle plane (see also Figs. 1 and 4).

Each deviation was a smooth bend that affected the geometry locally (Fig. 3). Three coronal planes were selected to position the septal deviations: an anterior, a middle, and a posterior plane (Fig. 1). The anterior plane was a cross-section through the nasal valve region, the middle plane was a cross-section through the anterior inferior turbinate, and the posterior plane was a cross-section through the posterior inferior turbinate (Fig. 1). Each computational model had a single septal deviation located in one of these three coronal planes and in one of the following three levels: inferior, middle, or superior level. Inferior deviations were located in the lower third of the cross-section, middle deviations were located in the middle third of the cross-section, and superior deviations were located in the upper third of the cross-section (Fig. 4).

All septal deviations reduced the cross-sectional area of the coronal plane where the deviation was positioned by 30 mm^2 (Table 1). This reduction of 30 mm^2 was applied to all deviations irrespective of the original cross-sectional area of the coronal plane where the deviation was located, to simulate septal deviations of the same magnitude. This strategy was chosen so that our simulations could be compared with the *in vivo* experiments of Cole and collaborators,[39,40] who inserted a fiber-foam slab at different locations in the nasal cavity of healthy individuals and used rhinomanometry to investigate how simulated septal deviations affect nasal resistance. The numerical value of 30 mm^2 was chosen to increase nasal resistance by >100%, as observed in patients with nasal obstruction due to septal deviations.[22,41,42] In terms of percentage reduction, the models with an anterior deviation had a 27% reduction in the cross-sectional area of the anterior plane, models with a middle deviation had an 18% reduction in the cross-sectional area of the middle plane, and models with a posterior deviation had a 21% reduction in the cross-sectional area of the posterior plane (Table 1).

Steady-state airflow simulations were conducted in Fluent 6.3.26 (ANSYS, Inc., Lebanon, NH) for airflow rates corresponding to a patient breathing at rest. Because an adult human breathes ~7.5 L/minute of air at rest,[43] the average inspiratory airflow rate was estimated as 125 mL/s per nostril, where it is assumed that the inhalation and exhalation phases of the breathing cycle have the same duration. The following boundary conditions were used in Fluent to determine the airflow field: (1) a "wall" condition (zero velocity) at the airway walls, (2) a "mass-flow-inlet" condition at the nostril, (3) a "pressure-outlet" condition at the outlet, and (4) a "symmetry" condition at the nasopharyngeal symmetry plane. The symmetry boundary condition led to convergence problems, which were addressed by reducing the underrelaxation factor of the momentum equation from

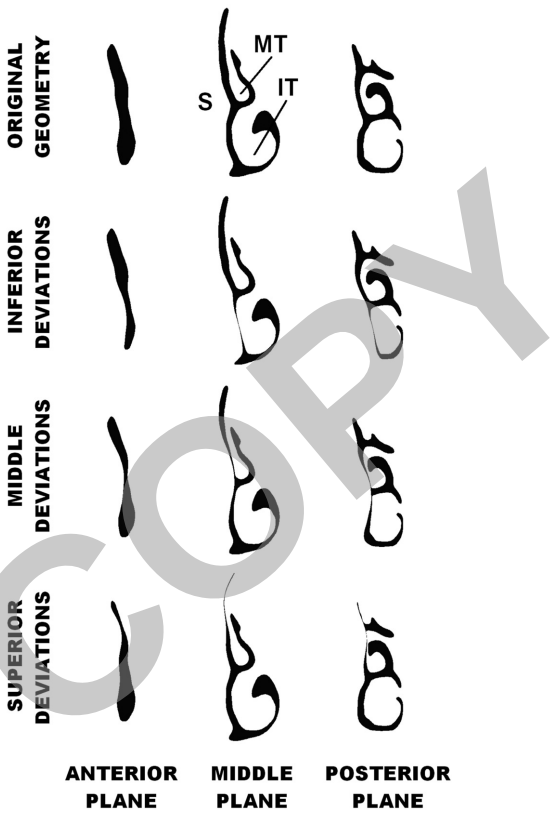

Figure 4. Each of the nine models with septal deviation had one single deviation located in one of three coronal planes (anterior, middle, or posterior plane) and one of three levels (inferior, middle, or superior third of the cross-section). All deviations reduced the cross-sectional area by 30 mm^2. (First Column) Anterior plane in the original model and in each of the three models with anterior deviations. (Second Column) Middle plane in the original model and in each of the three models with middle-plane deviations. (Third Column) Posterior plane in the original model and in each of the three models with posterior deviations. S, septum; IT, inferior turbinate; MT, middle turbinate. The airway is shown in black.

the default 0.7 to a new value of 0.3. Fluent took ~5 hours of computing time (~3000 iterations) to solve the equations. Convergence was confirmed by small residuals (continuity, $<10^{-4}$; velocities, $<5 \times 10^{-5}$) and by monitoring the pressure at the nostril surface for stabilization. Additional details on the differential equations, computational algorithms, and air physical properties used can be found in a previous publication by our group (Garcia *et al.* 2007).[35]

Finally, to evaluate how the computer-generated septal deviations modified the resistance of the nasal passages to inspiratory airflow, we computed the transnasal pressure drop (Δp) needed to maintain the breathing rate at Q = 125 mL/s. Nasal resistance (R_{nose}) was calculated as $R_{nose} = \Delta p/Q$. One should note that this definition is different from the convention in rhinomanometry studies, where nasal resistance is defined as the ratio $\Delta p/Q$ when Δp = 150 Pa.[42,44] The reasoning behind our definition of nasal resistance is that the breathing rate of an individual is determined by his/her metabolic needs, so that the lungs must adjust the inspiratory driving force (*i.e.*, Δp) to obtain the target breathing rate.

RESULTS

Our results revealed that the posterior nasal cavum can accommodate significant septal deviations without a substantial increase in airway resistance. All septal deviations increased nasal resistance

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Table 1 **Cross-sectional areas of the anterior, middle, and posterior planes (see Fig. 1) in the original geometry and in the models with a simulated septal deviation**

	Cross-Sectional Area		
Plane	**Original (mm^2)**	**After Septal Deviation (mm^2)**	**Reduction (%)**
Anterior	110	80	27
Middle	167	137	18
Posterior	143	113	21

The septal deviations reduced the cross-sectional area by 30 mm^2, which meant a greater percentage reduction in cross-sectional area in the models with anterior septal deviation.

by < 30%, except for the inferior deviation in the anterior plane, which increased nasal resistance by 124% (Fig. 5; Table 2). In each plane, inferior deviations increased nasal resistance the most, whereas superior deviations affected nasal resistance the least. This effect was much more marked in the anterior plane, where an inferior deviation more than doubled nasal resistance, while a superior deviation did not affect airway resistance at all. Conversely, the differences in airway resistance were much smaller in the posterior plane, where an inferior deviation increased nasal resistance by 26%, and a superior deviation increased nasal resistance by 13% (Fig. 5; Table 2).

These effects of the location of septal deviations on nasal resistance correlate with the airflow patterns in the original nasal geometry. In the anterior plane of the original nasal passage, airflow was concentrated in the lower half of the cross-section (Fig. 6) because of an anatomic notch in the vestibule that prevented inhaled airflow from reaching the superior part of the anterior nose (Fig. 7). As air traveled toward the back of the nose, it spread more uniformly across coronal cross-sections, so that a more uniform airflow distribution was observed in the middle and posterior planes (Figs. 6 and 7). Effectively, this meant that middle and posterior septal deviations did not increase nasal resistance substantially because air had more room to circumvent the septal deviation. In the anterior plane, on the other hand, the cross-sectional area was smaller (Table 1); thus, air currents had no easy way of avoiding the constriction, causing nasal resistance to increase sharply (Fig. 5).

DISCUSSION

There is much debate whether septal deviation impairs nasal physiology. It has been suggested that septal deviation is associated with several pathologies, including epistaxis,[45] impaired mucociliary clearance,[45,46] chronic nasal obstruction,[6] chronic sinusitis,[47,48] snoring,[49] and sleep apnea.[50] However, the evidence for such connections is still inadequate or controversial. For example, some authors have reported that patients with septal deviation are more likely to develop sinusitis,[48] while others have not found such an association.[47] The relationship between septal deformity and nasal obstruction is also unclear. Although a gross septal deviation is likely to cause obstruction, it is challenging to determine whether more subtle septal deviations result in patient perceptions of nasal obstruction. Because septal deviations are found in >20% of the healthy adult population according to studies of cranial CT scans, many deviations are not symptomatic and should be considered a normal anatomic variation.[2,51]

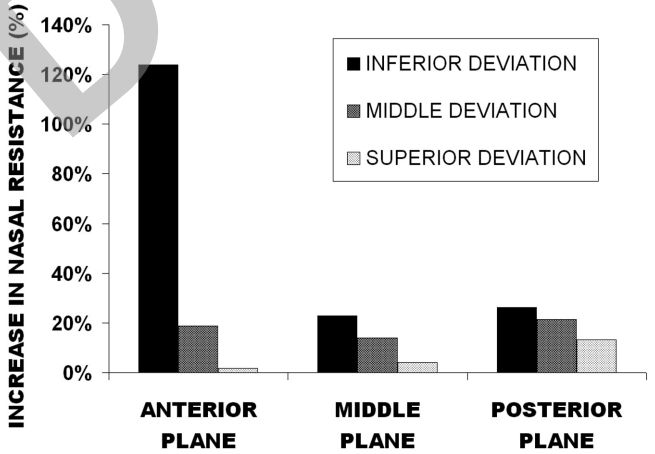

Figure 5. Percentage increase in nasal resistance in the nine models with septal deviation in relation to the original nasal geometry.

Reported surgical outcomes for septoplasty have been less than ideal.[7,10,52] Although failure rates as low as 12% have been reported,[11] most studies agree that 20–30% of patients undergoing a reportedly technically successful septoplasty have no postoperative relief of symptoms.[2,10] Recent studies suggested that the success rate deteriorates with time as the placebo effect fades.[2,6,7] One long-term study found that only 26% of the patients were symptom free 9 years after the operation.[12] These findings are supported by rhinomanometry studies that found no reduction in airway resistance after septoplasty[22,41,52] (although such reduction was observed by others[6,12,14]). Therefore, patient selection for septoplasty remains less than ideally defined.

Our airflow simulations suggest that the location of a septal deviation is an essential attribute that must be taken into account when assessing whether the deviation increases nasal resistance. In our model, a deformity located in the anterior nose increased nasal resistance markedly, while deviations in the cavum did not affect resistance appreciably. These results are strongly supported by rhinomanometry studies. Cole and colleagues inserted a fiber-foam slab at different locations in the nasal cavity of healthy individuals and studied how the location of the simulated septal deviation affected nasal resistance.[39,40] They concluded that the posterior nasal cavum can accommodate large septal deviations with little effect on airway resistance, while deviations in the anterior nose increased resistance severely. In the anterior nose, inferior deviations increased resistance more than superior deviations, in agreement with our simulations. Further evidence that anterior deviations are more relevant than posterior ones comes from studies that found that septoplasty is more effective in patients with anterior deviations.[7,9,53] The lower success rate in patients with posterior deviations suggests that the septal deviations in these patients may not have been the cause of symptomatic nasal obstruction.

The greater impact of anterior, rather than posterior, septal deviations on nasal resistance can be understood in terms of the nasal valve, which is the region between the limen nasi and the anterior end of the inferior turbinate.[54–56] According to rhinomanometry studies, nearly 50% of the total nasal resistance occurs 1.0–3.0 cm from the nostrils, warranting the name "nasal valve region" to this flow-limiting segment.[56] This region has also been shown to be the narrowest portion of the nasal passages.[57] due to its small cross-sectional area, narrowing the nasal valve region causes dramatic increases in

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Table 2 **Transnasal pressure drop (Δp) in each of the nine models with simulated septal deviation**

Location of the Septal Deviation		Δp (Pa)	Increase in R_{nose} in Relation to Original Model (%)
Plane	Level		
Anterior	Inferior	27.3	124
	Middle	14.5	19
	Superior	12.2	0
Middle	Inferior	15.0	23
	Middle	13.9	14
	Superior	12.7	4
Posterior	Inferior	15.4	26
	Middle	14.8	21
	Superior	13.8	13

The percentage increase in nasal resistance (R_{nose}) is given in relation to the original model, where Δp = 12.2 Pa.

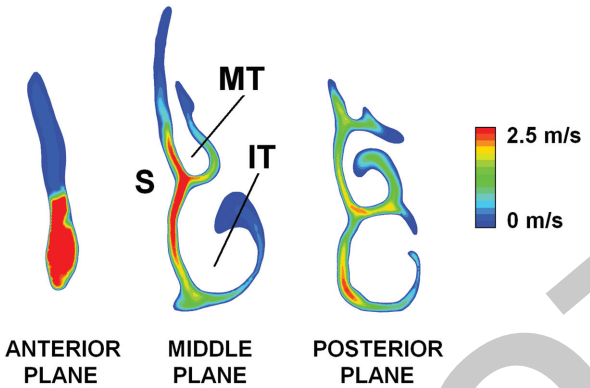

Figure 6. *Color maps of velocity magnitude in the anterior, middle, and posterior coronal planes of the original nasal model for an airflow rate corresponding to resting breathing. Note that the airflow is concentrated inferiorly in the anterior plane, while it is more evenly distributed in the middle and posterior planes. The scale of the color map was adjusted to improve visualization, so that air speeds above 2.5 m/s are shown in red. S, septum; IT, inferior turbinate; MT, middle turbinate.*

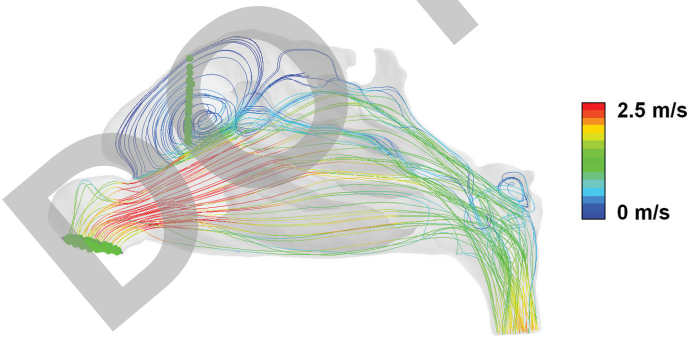

Figure 7. *Sagittal view of streamlines showing the airflow patterns in the original healthy nasal passage colored by velocity magnitude. Massless particles were released from the nostril and from a coronal plane in the nasal valve region (release points are marked by green dots). Note that the anatomic notch in the vestibule led to an eddy downstream of the notch. The scale of the color map was adjusted to improve visualization, so that air speeds above 2.5 m/s are shown in red.*

nasal resistance, as shown by Schreck and coworkers[58] using a plastic nasal replica. In our computational study, the anterior plane had the smallest cross-sectional area of the three planes investigated. Therefore, anterior septal deviations reduced the cross-sectional area by a greater percentage than septal deviations in the middle or posterior planes (Table 1). Airflow in the more posterior nasal cavity found alternate routes to circumvent the septal deviations, while airflow in the nasal valve had nowhere else to go and thus was forced to overcome the narrowed region (Figs. 6 and 7). Therefore, the greater effect of anterior, rather than posterior, septal deviations can be explained by the smaller cross-sectional area of the anterior nose and its role as a nasal valve.

The greater impact of inferior, rather than superior, septal deviations can be understood in terms of the airflow patterns inside the nose. The main air current in healthy nasal passages has been described as flowing near the nasal floor as well as between the inferior and middle turbinates and the septum.[59] In contrast, airflow in the superior nose (olfactory region) accounts for <15% of inhaled air.[28,60] Therefore, inferior septal deviations disturb nasal airflow patterns more than superior deviations, thus causing greater increases in nasal resistance (Fig. 5; Table 2).

The nasal geometry investigated in this study had an anatomic notch in the vestibule that prevented air from flowing through the superior portion of the anterior nose (Fig. 7), so that a superior deviation in the anterior plane did not affect nasal resistance at all (Fig. 5; Table 2). Although our research group has observed this anatomic feature in several other individuals, it is unclear whether this is a prevalent feature in the overall population. The presence of the notch, however, is not expected to have influenced the main conclusions in this paper, *viz.*, that anterior/inferior deviations affect nasal resistance more than posterior/superior deviations. As discussed previously, this behavior can be explained by the small cross-sectional area of the nasal valve region and by the low airflow rate in the olfactory region. In both regards, the nasal geometry investigated here is typical of a healthy nasal anatomy.[59]

Currently, there are no standard, objective criteria to evaluate nasal function. Patient selection for septoplasty by simple physical examination is inherently subjective and may not predict an ideal surgical outcome. In the 1980s, there was hope that rhinomanometry and acoustic rhinometry would provide the desired objective criteria. Unfortunately, these methods have some shortcomings and have not gained widespread acceptance or universal adoption. Limitations of rhinomanometry and acoustic rhinometry include (1) irreproducibility of measurements made on the same patient on different days, (2) poor correlation between these objective measures of airflow and the patient's subjective assessment of nasal patency, and (3) dependence of accurate measurements on the experience level of the technician.[6,8,11,22,57,61,62] Therefore, several authors have called for the development of new objective methods to evaluate nasal physiology.[2,9,22] There is hope that computational models built from patient-specific CT scans may fill this gap.[23]

The results presented in this article provide evidence that CFD-predicted nasal resistance is in good agreement with past clinical

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observations, thus supporting the expectation that in the future, computational tools may be used to select those patients who will benefit from surgery. However, it will take years before this technology becomes feasible in a clinical setting because, currently, it is too expensive and labor intensive. To become a widespread tool to plan nasal surgeries, specific CFD software must be developed. Such software will need to be faster and more user-friendly than those currently available in the market. For instance, the methodology used in this article required considerable training in fluid mechanics and used four different software products: Mimics (to extract the 3D nasal geometry from CT scans), ICEM-CFD (to build computational meshes), Sculptor (to modify the nasal geometry virtually), and Fluent (to solve the differential equations and analyze the results). To become a widespread tool for surgical planning, CFD software products such as these must be combined into a single platform with an affordable price so that this technology can be available to physicians.

Meanwhile, the current technology is being used in research institutions to investigate the interplay between nasal physiology and fluid mechanics. A major strength of CFD modeling is the ability to alter the shape of the nasal passages in a virtual setting to study how geometry affects function. In other words, CFD modeling allows the researcher to isolate a variable (nasal geometry) to investigate its effect in nasal physiology (airway resistance), thus removing the confounding effects of other parameters that are inherently variable in *in vivo* studies. Another strength of CFD modeling is its ability to probe other nasal functions, such as the accessibility of odorant molecules to the olfactory epithelia and humidification, heating, and filtration of inspired air. Recently, some suggestive studies have been published that illustrate the potential of CFD modeling. Garcia and collaborators[35] found higher-than-normal mucus evaporation rates in a model of a patient with atrophic rhinitis, supporting their hypothesis that mucus dehydration is at the root of atrophic rhinitis disease. Zhao and collaborators[37] showed that small changes in the shape of the nasal valve region may affect significantly the delivery of odorant molecules to the olfactory epithelia. Elad and collaborators[34] investigated the shear stresses caused by nasal airflow and speculated that paradoxical feelings of nasal obstruction in an otherwise normal nose may be related to abnormal shear stress levels sensed by mechanoreceptors in the nasal mucosa. Therefore, although widespread use of CFD software to plan nasal surgeries still is not a reality, CFD modeling is being used by research institutions to elucidate how nasal physiology and fluid mechanics are interconnected.

We must note that the definition of nasal resistance adopted in this study yields absolute values that are different from those obtained *via* rhinomanometry. Nasal resistance in the computational model without septal deviation was $\Delta p/Q$ = (12.2 Pa)/(250 mL/s) = 0.05 Pa·s/mL), which is lower than the range of 0.15–0.30 Pa·s/mL reported in rhinomanometry studies.[63] This difference is caused by the nonlinear nature of the pressure–flow relationship. Garcia and collaborators,[64] performing measurements in plastic nasal replicas, showed that transnasal pressure drop (Δp) increases with airflow rate (Q) according to the equation $\Delta p = aQ^b$, where the constant a varies from subject to subject, while the exponent $b \approx 1.75$. Nasal resistance is the slope of the pressure–flow curve ($\Delta p/Q$); therefore, its value varies depending on what Q (or Δp) is used to perform the measurements. Because the standard in rhinomanometry studies is to measure nasal resistance at a transnasal pressure drop of 150 Pa,[42,44] the nasal resistance values reported in this study are lower than those reported in rhinomanometry studies. To illustrate this, let us use the experimental relationship $\Delta p = (4.6 \pm 0.6) \times 10^7\ Q^{1.79 \pm 0.02}$, where Δp is in pascals and Q is in cubic meters per second, reported for one plastic replica of a healthy nose.[64] For this particular nasal geometry, nasal resistance is 0.07 Pa·s/mL at Q = 250 mL/s and 0.17 Pa·s/mL at 150 Pa, thus illustrating that very different absolute values of nasal resistance are obtained depending on what value of Δp or Q is used to define nasal resistance. These definition differences, however, do not affect the results reported here (*i.e.*, how the location of septal deviations affect nasal resistance) because a consistent definition was used throughout the study.

Finally, the following limitations of this study should be acknowledged. First, our results are based on the nasal anatomy of a single individual. A larger sample size needs to be studied to determine whether the results reported here remain true when interindividual variability in nasal geometry is taken into account. Second, the position of the turbinates was kept fixed and only the septum was moved to create septal deviations. In reality, however, the geometry of the lateral wall is affected by septal deviations, the turbinates being usually larger in the concave side and smaller in the convex side of the septum.[65] Thus, one should keep in mind that, rather than focusing on the specific numbers generated by our simulations, the goal of this study was to develop general principles of how the location of septal deviations affects nasal resistance. A third limitation of our study is that we did not include in the model the nasal passage contralateral to the septal deviation. In reality, airflow is split between the left and right nasal passages, so that if one nasal passage is blocked air will tend to flow through the contralateral side. Therefore, our results describe the relationship between septal deviation and *unilateral* nasal resistance. Future studies should include the anatomic changes that take place in the contralateral side (*i.e.*, turbinate hypertrophy) to investigate the relationship between septal deviation and total nasal resistance.

CONCLUSIONS

Our computational results suggest some general principles that may help distinguish between physiological and pathological septal deviations. The posterior nasal cavity can accommodate large septal deviations without increasing nasal resistance appreciably. In contrast, septal deviations in the nasal valve region are more likely to increase airway resistance. The impact of a septal deviation on airway resistance can be understood in terms of how much space airflow has to circumvent the deviation to find alternate routes within the nose. Finally, this study shows that CFD simulations provide predictions of nasal resistance that mimic *in vivo* observations using rhinomanometry. In the future, computational modeling may be used as a tool to select patients that benefit the most from septoplasty, plan patient-specific surgeries, and optimize surgical outcome.

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REFERENCES

1. Vainio-Mattila J. Correlations of nasal symptoms and signs in random sampling study. Acta Otolaryngol Suppl 318:1–48, 1974.
2. Roblin DG, and Eccles R. What, if any, is the value of septal surgery? Clin Otolaryngol Allied Sci 27:77–80, 2002.
3. Calhoun KH, Waggenspack GA, Simpson CB, et al. CT evaluation of the paranasal sinuses in symptomatic and asymptomatic populations. Otolaryngol Head Neck Surg 104:480–483, 1991.
4. Jones NS, Strobl A, and Holland I. A study of the CT findings in 100 patients with rhinosinusitis and 100 controls. Clin Otolaryngol Allied Sci 22:47–51, 1997.
5. Min YG, Jung HW, and Kim CS. Prevalence study of nasal septal deformities in Korea: Results of a nation-wide survey. Rhinology 33:61–65, 1995.
6. Singh A, Patel N, Kenyon G, et al. Is there objective evidence that septal surgery improves nasal airflow? J Laryngol Otol 120:916–920, 2006.
7. Konstantinidis I, Triaridis S, Triaridis A, et al. Long term results following nasal septal surgery. Focus on patients' satisfaction. Auris Nasus Larynx 32:369–374, 2005.

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8. Ho WK, Yuen AP, Tang KC, et al. Time course in the relief of nasal blockage after septal and turbinate surgery: A prospective study. Arch Otolaryngol Head Neck Surg 130:324–328, 2004.
9. Dinis PB, and Haider H. Septoplasty: Long-term evaluation of results. Am J Otolaryngol 23:85–90, 2002.
10. Jackson LE, and Koch RJ. Controversies in the management of inferior turbinate hypertrophy: A comprehensive review. Plast Reconstr Surg 103:300–312, 1999.
11. Pirila T, and Tikanto J. Unilateral and bilateral effects of nasal septum surgery demonstrated with acoustic rhinometry, rhinomanometry, and subjective assessment. Am J Rhinol 15:127–133, 2001.
12. Jessen M, Ivarsson A, and Malm L. Nasal airway resistance and symptoms after functional septoplasty: Comparison of findings at 9 months and 9 years. Clin Otolaryngol Allied Sci 14:231–234, 1989.
13. Mertz JS, McCaffrey TV, and Kern EB. Objective evaluation of anterior septal surgical reconstruction. Otolaryngol Head Neck Surg 92: 308–311, 1984.
14. Broms P, Jonson B, and Malm L. Rhinomanometry. IV. A pre- and postoperative evaluation in functional septoplasty. Acta Otolaryngol 94:523–529, 1982.
15. Sipila J, and Suonpaa J. A prospective study using rhinomanometry and patient clinical satisfaction to determine if objective measurements of nasal airway resistance can improve the quality of septoplasty. Eur Arch Otorhinolaryngol 254:387–390, 1997.
16. Simola M, and Malmberg H. Sensation of nasal airflow compared with nasal airway resistance in patients with rhinitis. Clin Otolaryngol Allied Sci 22:260–262, 1997.
17. Grymer LF, Hilberg O, Elbrond O, et al. Acoustic rhinometry: Evaluation of the nasal cavity with septal deviations, before and after septoplasty. Laryngoscope 99:1180–1187, 1989.
18. Jessen M, Köpman A, and Malm L. Selection with and without rhinomanometry of patients for septoplasty. Am J Rhinol 3:201–203, 1989.
19. Yaniv E, Hadar T, Shvero J, et al. Objective and subjective nasal airflow. Am J Otolaryngol 18:29–32, 1997.
20. Kim CS, Moon BK, Jung DH, et al. Correlation between nasal obstruction symptoms and objective parameters of acoustic rhinometry and rhinomanometry. Auris Nasus Larynx 25:45–48, 1998.
21. Reber M, Rahm F, and Monnier P. The role of acoustic rhinometry in the pre- and postoperative evaluation of surgery for nasal obstruction. Rhinology 36:184–187, 1998.
22. Courtiss EH, and Goldwyn RM. The effects of nasal surgery on airflow. Plast Reconstr Surg 72:9–21, 1983.
23. Bailie N, Hanna B, Watterson J, et al. An overview of numerical modelling of nasal airflow. Rhinology 44:53–57, 2006.
24. Shi H, Kleinstreuer C, and Zhang Z. Laminar airflow and nanoparticle or vapor deposition in a human nasal cavity model. J Biomech Eng Trans ASME 128:697–706, 2006.
25. Zamankhan P, Ahmadi G, Wang ZC, et al. Airflow and deposition of nano-particles in a human nasal cavity. Aerosol Sci Technol 40:463–476, 2006.
26. Inthavong K, Tian ZF, Li HF, et al. A numerical study of spray particle deposition in a human nasal cavity. Aerosol Sci Technol 40:1034–1045, 2006.
27. Keyhani K, Scherer PW, and Mozell MM. Numerical simulation of airflow in the human nasal cavity. J Biomech Eng 117:429–441, 1995.
28. Subramaniam RP, Richardson RB, Morgan KT, et al. Computational fluid dynamics simulations of inspiratory airflow in the human nose and nasopharynx. Inhal Toxicol 10:91–120, 1998.
29. Croce C, Fodil R, Durand M, et al. In vitro experiments and numerical simulations of airflow in realistic nasal airway geometry. Ann Biomed Eng 34:997–1007, 2006.
30. Ozlugedik S, Nakiboglu G, Sert C, et al. Numerical study of the aerodynamic effects of septoplasty and partial lateral turbinectomy. Laryngoscope 118:330–334, 2008.
31. Lindemann J, Keck T, Wiesmiller KM, et al. Numerical simulation of intranasal air flow and temperature after resection of the turbinates. Rhinology 43:24–28, 2005.
32. Lindemann J, Leiacker R, Sikora T, et al. Impact of unilateral sinus surgery with resection of the turbinates by means of midfacial degloving on nasal air conditioning. Laryngoscope 112:2062–2066, 2002.
33. Naftali S, Rosenfeld M, Wolf M, et al. The air-conditioning capacity of the human nose. Ann Biomed Eng 33:545–553, 2005.
34. Elad D, Naftali S, Rosenfeld M, et al. Physical stresses at the air–wall interface of the human nasal cavity during breathing. J Appl Physiol 100:1003–1010, 2006.
35. Garcia GJM, Bailie N, Martins DA, et al. Atrophic rhinitis: A CFD study of air conditioning in the nasal cavity. J Appl Physiol 103:1082–1092, 2007.
36. Zhao K, Pribitkin EA, Cowart BJ, et al. Numerical modeling of nasal obstruction and endoscopic surgical intervention: Outcome to airflow and olfaction. Am J Rhinol 20:308–316, 2006.
37. Zhao K, Scherer PW, Hajiloo SA, et al. Effect of anatomy on human nasal air flow and odorant transport patterns: Implications for olfaction. Chem Senses 29:365–379, 2004.
38. Pless D, Keck T, Wiesmiller KM, et al. Numerical simulation of airflow patterns and air temperature distribution during inspiration in a nose model with septal perforation. Am J Rhinol 18:357–362, 2004.
39. Cole P, Chaban R, Naito K, et al. The obstructive nasal septum. Effect of simulated deviations on nasal airflow resistance. Arch Otolaryngol Head Neck Surg 114:410–412, 1988.
40. Chaban R, Cole P, and Naito K. Simulated septal deviations. Arch Otolaryngol Head Neck Surg 114:413–415, 1988.
41. Ricci E, Palonta F, Preti G, et al. Role of nasal valve in the surgically corrected nasal respiratory obstruction: Evaluation through rhinomanometry. Am J Rhinol 15:307–310, 2001.
42. Cole P. Nasal airflow resistance: A survey of 2500 assessments. Am J Rhinol 11:415–420, 1997.
43. Annals of the ICRP 24. ICRP (International Commission on Radiological Protection) Publication 66. Human Respiratory Tract Model for Radiological Protection. Oxford: Pergamon Press, 23, 1994.
44. Calhoun KH, House W, Hokanson JA, et al. Normal nasal airway-resistance in noses of different sizes and shapes. Otolaryngol Head Neck Surg 103:605–609, 1990.
45. Blaugrund SM. Nasal obstruction. The nasal septum and concha bullosa. Otolaryngol Clin North Am 22:291–306, 1989.
46. Jang YJ, Myong NH, Park KH, et al. Mucociliary transport and histologic characteristics of the mucosa of deviated nasal septum. Arch Otolaryngol Head Neck Surg 128:421–424, 2002.
47. Harar RP, Chadha NK, and Rogers G. The role of septal deviation in adult chronic rhinosinusitis: A study of 500 patients. Rhinology 42: 126–130, 2004.
48. Elahi MM, and Frenkiel S. Septal deviation and chronic sinus disease. Am J Rhinol 14:175–179, 2000.
49. Elsherif I, and Hussein SN. The effect of nasal surgery on snoring. Am J Rhinol 12:77–79, 1998.
50. Silvoniemi P, Suonpaa J, Sipila J, et al. Sleep disorders in patients with severe nasal obstruction due to septal deviation. Acta Otolaryngol Suppl 529:199–201, 1997.
51. Gray LP. Deviated nasal septum. Incidence and etiology. Ann Otol Rhinol Laryngol Suppl 87:3–20, 1978.
52. Constantian MB, and Clardy RB. The relative importance of septal and nasal valvular surgery in correcting airway obstruction in primary and secondary rhinoplasty. Plast Reconstr Surg 98:38–54, 1996.
53. Grutzenmacher S, Robinson DM, Grafe K, et al. First findings concerning airflow in noses with septal deviation and compensatory turbinate hypertrophy—A model study. ORL J Otorhinolaryngol Relat Spec 68:199–205, 2006.
54. Haight JS, and Cole P. The site and function of the nasal valve. Laryngoscope 93:49–55, 1983.
55. Hirschberg A, Roithmann R, Parikh S, et al. The airflow resistance profile of healthy nasal cavities. Rhinology 33:10–13, 1995.
56. Wexler DB, and Davidson TM. The nasal valve: A review of the anatomy, imaging, and physiology. Am J Rhinol 18:143–150, 2004.
57. Roithmann R, Cole P, Chapnik J, et al. Acoustic rhinometry, rhinomanometry, and the sensation of nasal patency: A correlative study. J Otolaryngol 23:454–458, 1994.
58. Schreck S, Sullivan KJ, Ho CM, et al. Correlations between flow resistance and geometry in a model of the human nose. J Appl Physiol 75:1767–1775, 1993.
59. Wolf M, Naftali S, Schroter RC, et al. Air-conditioning characteristics of the human nose. J Laryngol Otol 118:87–92, 2004.

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60. Kelly JT, Prasad AK, and Wexler AS. Detailed flow patterns in the nasal cavity. J Appl Physiol 89:323–337, 2000.
61. Carney AS, Bateman ND, and Jones NS. Reliable and reproducible anterior active rhinomanometry for the assessment of unilateral nasal resistance. Clin Otolaryngol Allied Sci 25:499–503, 2000.
62. Tomkinson A, and Eccles R. The identification of the potential limitations of acoustic rhinometry using computer-generated, three-dimensional reconstructions of simple models. Am J Rhinol 10:77–82, 1996.
63. Moore EJ, and Kern EB. Atrophic rhinitis: A review of 242 cases. Am J Rhinol 15:355–361, 2001.
64. Garcia GJ, Tewksbury EW, Wong BA, et al. Interindividual variability in nasal filtration as a function of nasal cavity geometry. J Aerosol Med Pulm Drug Deliv 22:139–155, 2009.
65. Uzun L, Savranlar A, Beder LB, et al. Enlargement of the bone component in different parts of compensatorily hypertrophied inferior turbinate. Am J Rhinol 18:405–410, 2004. □

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